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TITLE: Upgrade of LLU Proton Synchrotron and Switchyard for Performing Beam Scanning of Large Irregular Targets in Human Patients with Cancer

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Optimal proton radiation treatment of tumors having broad regional-disease patterns of spread places specific design requirements on the synchrotron and switchyard at Loma Linda University Medical Center. The purpose of this project is to perform engineering upgrades to the synchrotron accelerator and switchyard to permit the delivery of therapeutic proton radiation with the essential beam characteristics needed to treat such tumors. The modified design will permit modulation of beam energy on a spill-to-spill basis and delivery of uniform beam intensity over an extended extraction period. The project scope includes enhancing the extracted beam intensity control; developing software applications to provide dynamic accelerator energy changes for achieving spill-to-spill beam delivery; and developing an integrated fast beam cut-off system to safely inhibit proton beam from scanning outside the targeted volume. To date, significant progress has been achieved on most of the major tasks described in the grant proposal, including development of hardware and software requirement specifications and design documents. The research and design work for the remaining tasks will be completed in the first half of next year, and system integration will follow.

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## Table of Contents

Cover........................................................................................ 1

SF 298........................................................................................ 2

Introduction........................................................................................ 4

Body........................................................................................ 4

Key Research Accomplishments........................................................12

Reportable Outcomes........................................................................12

Conclusions........................................................................................12

References........................................................................................12

Appendices........................................................................................13

## INTRODUCTION

The broad purpose of this and other engineering projects planned and currently underway at Loma Linda University Medical Center (LLUMC) is to enhance the efficacy of proton radiation therapy and to expand the range of diseases that can be treated by this modality. Before LLUMC built the world's first hospital-based proton treatment center in 1990, proton therapy was limited to a small set of tumor types and a non-clinical setting. During the last decade LLUMC has treated over 6000 patients with proton therapy in a hospital environment, and in the process has expanded the range of treatment protocols dramatically [1-9]. If LLUMC is to treat new types of tumors having broad regional disease spread , such as breast, lung, and lymphoma tumors, significant upgrades must be made to the facility's technology.

To deliver the proton beam to large irregular targets with high precision requires the use of rapid and precise variable energy changes. This project will provide for variable-energy enhancements of the accelerator and transport system (not for the treatment room).The engineering upgrades to be performed will permit modulation of beam energy on a spill-to-spill basis and delivery of uniform beam intensity over an extended extraction period.

These goals are stated broadly in the STATEMENT OF WORK in the original proposal as follows:

> Objective 1: Upgrade the LLU proton synchrotron to maximize beam intensity and create slow extraction capabilities, producing a stable beam of uniform intensity to satisfy beam-scanning requirements.
>
> Objective 2: Upgrade the switchyard to be capable of responding to the variable energy beam characteristics and efficiently deliver the beam to each treatment room.

The specific tasks involved in achieving these objectives are better described in the METHODS section of the original proposal than in the STATEMENT OF WORK. Therefore, the progress on this project will be described below with reference to the specific tasks outlined in the METHODS section.

## BODY

The plan of work in the original proposal was broken down into 9 tasks in the METHODS section (tasks a through i). Progress on each task will be described separately. Please refer to the Gantt chart on page 11 for project timeline statuses.

a. Enhance the synchrotron extracted beam intensity control to provide uniform extracted proton beam intensity from the accelerator with the goal of +/- 5% uniformity and an intensity selection range of 20 to 1.

1. Develop an injected beam intensity control system via debuncher in the injection line.

2. Develop instrumentation for monitoring and verifying correct beam intensity within the synchrotron ring for each accelerator cycle.

(Tasks a1 and a2 have been combined into a single project and will be described as such).

The primary goal of the Injected Intensity project is to control and measure the quantity of protons injected into the accelerator every cycle. The control will be accomplished by adjusting the phase of the RF field in the debuncher cavity through a software interface that will run automatically in the background. Currently the controls for the debuncher are manual dials. Hardware will be required to allow the software to control the debuncher.

The measurements will be accomplished by sampling the signals coming from the current torroids in the injection line and ring at specific times. The injection level will then be compared in software with the level that was requested in the treatment plan. If it is not within tolerance, the spill will be aborted. Hardware will be required to condition and sample the signals from the current torroids.

<u>Work performed to date:</u>

- A study was completed that determined the transfer function between the current from the dipole holec and the ring frequency.

- A study was completed showing that the RF phase shift control of the debuncher was able to control the injected intensity over the required range.

- Hardware was tested to make sure that it could sample data fast enough and in the correct sequence to meet safety requirements. Based on the results we were able to specify the hardware required for the project.

- The software algorithm was tested to make sure that it could do the required calculations within the time constraints of the safety requirements.

Proof of concept studies are complete. The software and hardware prototypes of the control system are complete and testing and data collection will begin soon.

3. Develop enhancements of dipole magnet power supplies that will provide dynamic response for reducing ripple, thereby improving the stability of the extracted beam.

The objective of this task is to reduce the noise and ripple of the magnetic field in the ring dipoles to levels that enable beam stacking. This will be accomplished by upgrading the "E" supplies.

Work performed to date:

A study performed demonstrated that the noise and ripple can be dramatically reduced by synchronizing the SCR firing to a time base instead of synchronizing to multiple zero crossing points.

4. Develop enhancements of ring quadrupole magnet power supplies that will provide dynamic response for reducing ripple and improving stability.

A modified design will improve stability of the quadrupole field in the accelerator ring during extraction. This will include reducing the 400Hz ripple in the "D" supplies.

Work performed to date:

This project will be performed in year 2.

5. Add extracted beam intensity detector for use in feedback system for enhancing control and uniformity of beam spill.

For beam scanning to function it must be able to deliver a specific dose to an area. This occurs in one of two ways: dose per time is controlled at the accelerator, or dwell time per area is controlled by the scanning magnets. The drawback of changing dwell time is that the maximum speed of the scanning magnets must be slowed whenever extraction exceeds the average rate.

The extraction intensity control monitors and controls the extraction of protons from the accelerator to control dose extracted per time. This will allow the scanning magnets to function closer to their maximum scanning frequency. Higher scanning frequency will allow for multiple scans delivering less dose in the same time. This delivers the same dose but allows for greater averaging so that small intensity fluctuations become even smaller.

This task will allow any arbitrary extraction profile command to be realized provided the extraction profile does not require bandwidth higher than the extraction intensity control system. A static command will be used, but the system is built to support future commands that change within a given layer. This will allow greater control of delivered dose.

Work performed to date:

- Produced controllable extraction (not limited to specific shape).
- Suppressed extraction indefinitely (Previous record ~50ms).
- Controlled 500 ms extraction. (additional time for scanning up from 150 ms)
- Produced better signal-to-noise bandwidth product than the Fermi model.

b. Implement improved control of the 10-degree bending magnet downstream of the beam dump. Integrate a shunt magnet power supply into the beam transport control system to provide independent precision adjustment of beam transport extraction magnet, thus eliminating complex trim magnet corrections throughout the remaining transport system.

At present, a pair of bending magnets between the accelerator and the beam transport line are both controlled by the same power supply. Because the magnets having a common power source, the amount of beam-steering capability through this pair is limited. This project will add a second power supply to shunt current away from the second of the two magnets, thus allowing steering at an additional point within the pair and reducing the need for compensating steering magnets farther down the beamline.

Work performed to date:

Testing has verified that the addition of this magnet will reduce the need for compensating magnets. The requirements and design specifications have been completed, and integration will begin soon.

c. Develop software applications to provide dynamic accelerator energy changes for achieving spill-to-spill beam delivery. Also perform interpolation of magnet ramps from small set of discrete energies to achieve continuously-variable energy capability.

In order to implement active beam scanning (Bragg-peak stacking), the PBTS must support a wide range of energies it is capable of delivering in one treatment. The purpose of this task is to modify the existing software control system to support multiple segments in one beam delivery process. The modified software pre-calculates the necessary parameters for all specified segments and distributes the information between all modules in the PBTS. The Segment List also contains multi-leaf collimator information to support future multi-leaf collimator devices.

Work performed to date:

- Developed calibration factors interpolation algorithm based on energy, intensity, cone size, scatter 1 and 2 positions
- Developed treatment parameter distribution and verification and selection protocol

- New software is capable of:
  - Configuring one or more energies from a palette of 18000 in one delivery
  - Stacking Bragg-peaks, allowing for more precise treatments without modulator propeller; and
  - Delivering multi-leaf collimator protocols (not supported by hardware), which would allow delivery of an arbitrarily shaped fields without manufacturing of apertures.
- System supports active scanning protocols (not supported by hardware, additional software modules required to control new hardware), allowing precision treatments without passive beam degrading devices.

d. Develop an integrated fast beam cut-off system to safely inhibit proton beam from scanning outside targeted volume. Develop a hardwired system capable of delivering proton beam within approximately 100 μsec of planned request and will allow beam delivery to be quickly interrupted as needed to end normal active beam delivery, as well as terminate beam under unsafe conditions.

Beam scanning produces a much more intense beam spot than passive scattering, requiring faster abort capability. The abort system protects the patient from unintended radiation. This "abort" signal will be produced by the selection verification portion of the safety system. The actuator will be an existing single-turn magnet that was designed for fast-abort but was never integrated into the control system.

<u>Work performed to date:</u>

Initial work has focused on fixing the existing fast abort device, locating its documentation and defining the interface between it and the new selection verification board. New firmware has been written for the new selection verification board, which will allow it to interface with the fast abort device.

e. Perform the synchrotron sextupole magnet installation.

This task will not be performed under this proposal. The sextupoles were purchased and installed using non-DOD funding.

f. Implement design of an accelerator control console providing ergonomic display equipment layout and integrated equipment racks and control cabling.

This task includes the modeling of the key equipment, racks, and associated hardware; establishing and documenting the new equipment layout and associated schematic changes; and procuring and installing this new equipment

<u>Work performed to date:</u>

This project is still in early preliminary design stages. The basic component modeling has been completed and preliminary layouts are underway.

g. Develop test and diagnostic utilities with graphical user interface to ensure proper functioning of the accelerator timing system and the beam profile detectors (Multi-Segmented Ion Chambers) in the switchyard.

In order to minimize the time to recognize, locate and fix a system failure (in a component, embedded system, or functional area), a set of diagnostic graphical user interfaces is being created for use by field service personnel.

Work performed to date:

The following utilities have been developed:

- Detector System Diagnostic – provides set of commands necessary to troubleshoot the detector system, including Recycling Integrator, Preset Scalar boards, detector state machine, proctor and monitor.
- Power Supply System Diagnostic – includes commands to set, read and modify settings for arbitrary power supplies. Shows operating parameter values not otherwise available through treatment tools
- MSIC/MWIC diagnostic application – troubleshoots Multi-Segment Ion Chambers and Multi-Wire Ion Chamber devices.
- Gantry Motion System Diagnostic Application – allows users to issue various commands associated with gantry motion system
- Motions Systems Diagnostic Application – services motion devices in the treatment nozzle (x-ray tube, scatterer 1, scatterer 2, modulation wheel propeller, etc.)
- VME bus Clock Generator Diagnostic Application – programs and verifies VCG board (PBTS timing system)
- VME bus Clock Timer Diagnostic Application – programs and verifies VCT board (PBTS timing system)
- VxWorks™ Monitor Diagnostic Application – monitors dynamic memory in VME creates
- High Voltage System Diagnostic Application – provides range of commands necessary to set, monitor and troubleshoot the high voltage supplies for the detector electronics.
- Selection Verification Diagnostic Application – services selection verification board
- Dipole Switch Controller Diagnostic Application – services DSC board.

h. Develop an accelerator and beam transport control system configuration management tool for maintaining control settings and limits for treatment, calibration and commissioning modes of operation.

The goal of the Proton Beam Therapy System Configuration Management System is to maintain control settings and limits for treatment and non-treatment modes of operation while maintaining data integrity. It provides a WIMP (Windows, Icon, Mouse, Pointer) Graphical User Interface for user-friendly interaction with the system.

The system requires user authentication and distinguishes between privileges for each of the authorized users. Authorized users have permissions to propose changes to the treatment data set or apply changes to non-treatment sets. The Clinical Configuration Manager has the responsibility of approving or rejecting proposed changes to treatment data. This system will improve reliability by providing a mechanism for maintaining data integrity.

In the current system, if the configuration tool is offline, beam delivery is prevented to any of the nozzles. The PBTS Configuration Management System will minimize downtime by eliminating this single point failure.

<u>Work performed to date:</u>

The requirements, design, and initial code development are complete. The project is currently in detailed testing mode.

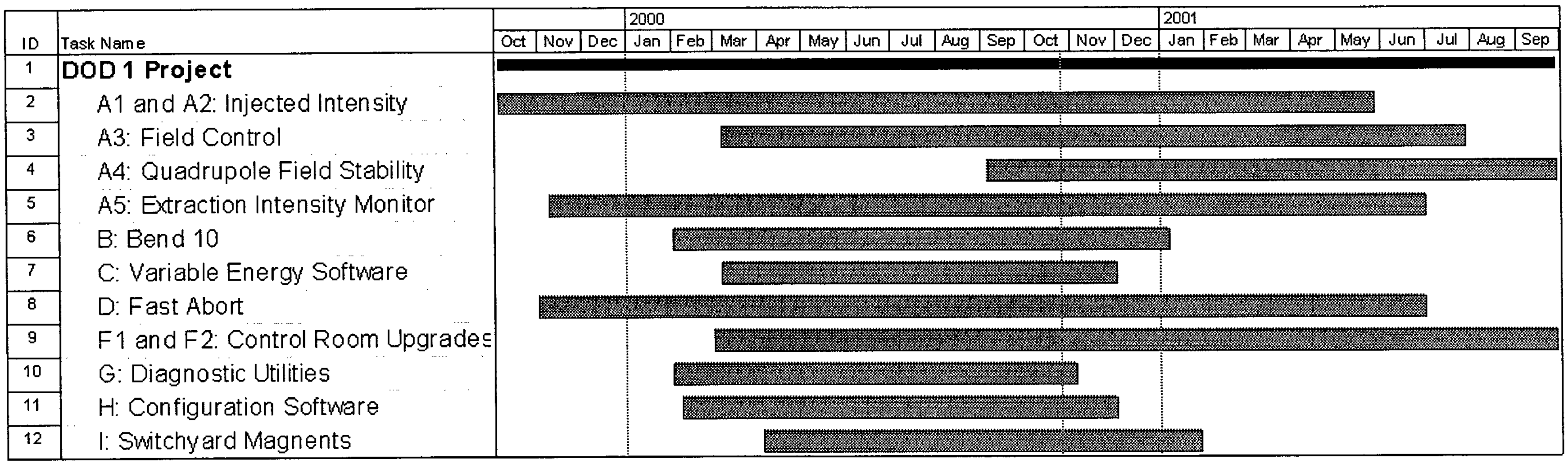
i. Enhance the beam transport magnet power supply and electronic control system command and readback accuracy and repeatability needed for precision active beam treatments.

Effective beam scanning requires a change in the field of the dipole magnets from spill to spill. The work on this task is aimed at making the power supplies regulate current better, change current faster and readback current more accurately.

<u>Work performed to date:</u>

The work done so far has allowed better response from the switchyard dipoles, better frequency response from the switchyard quadrupole supplies and better offset, gain and readback from the trim magnet supplies

# Figure 1: Project Schedule



## KEY RESEARCH ACCOMPLISHMENTS

- Completion of proof-of-concept studies on injected intensity project.
- Completion of software and hardware prototypes for injected intensity project.
- Completion of proof-of-concept studies for noise and ripple reduction.
- Produced controllable extraction; extended extraction period.
- Significant development of control software for variable energy.
- Development of firmware for selection verification device for fast-abort system.
- Significant development of test and diagnostic utilities software.
- Improved response of switchyard dipoles, switchyard quadrupole supplies, and trim magnet supplies.

## REPORTABLE OUTCOMES

N/A

## CONCLUSIONS

Work on most of the tasks is underway. Requirements and design work has been completed on most of the open tasks. It is anticipated that the proposed work will be completed on schedule.

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## APPENDICES

Appendix A: PBTS Configuration Management System Software Failure Modes and Effects Analysis (Document #3001496)

Appendix B: A, B, C type power supply analysis (Document #2001779 Rev B)

The appendices referenced above are attached to the end of this document. Additional requirements specifications, design documents, and other analyses supported by this project are available upon request, including:

- Injected Intensity Software Development Plan (Document #3001147)
- Injected Intensity Software Requirement (Document #3001148)
- Injected Intensity Software Test Plan (Document #3001149)
- Injected Intensity Software Design Document (Document #3001150)
- Injected Intensity Control Sub-System Requirement Specification (Document #2001694)
- Injected Intensity Instrumentation and Beam Inhibit Sub-System Requirement Specification (Document #2001694)
- *White Paper*: Inquiry For a Revised Configuration Management System. (Addresses the needs of a PBTS configuration management system).
- *White Paper*: Database Study. (Identifies the available options for data storage and the pros and cons of those options).
- PBTS Configuration Management System SRS (Document #3001447)
- PBTS Configuration Management System STP (Document #3001485)
- PBTS Configuration Management System HDD (Document #3001486)
- PBTS Configuration Management System SDD (Document #3001514)
- High level variable energy system software requirements specification
- Revised software requirements specifications for existing modules
- High level software design for variable energy system
- Revised detailed design documentation for existing modules
- Implementation (for newly created modules and revised code for existing ones)
- Test Plan, Test Case Specification, Test Scripts and Test validation reports for entire variable energy related software modules

# APPENDIX A

Optivus Technology, Inc.

Department Of Defense

PBTS Configuration Management System

# Software Failure Modes and Effects Analysis

Document No.: 3001496
Revision: A

# Revision History

| Date | Revision | Description | Author |
|---|---|---|---|
| 03/1/00 | XA | Initial Version | Dana Salem |
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| | | | |

# TABLE OF CONTENTS


1.0 PURPOSE ........ 1

2.0 SCOPE OF DOCUMENT ........ 1

3.0 REFERENCE DOCUMENTS ........ 1

4.0 DEVELOPING THE FAILURE MODES AND EFFECTS CATALOG ........ 1

5.0 OCCURRENCE LEVELS AND SEVERITY CATEGORIES ........ 1

6.0 FAILURE MODE MITIGATION ........ 5

7.0 SUMMARY ........ 5

## 1.0 Purpose

The purpose of this document is to evaluate the safety aspects of the Proton Beam Treatment System (PBTS) configuration system software through a failure modes and effects analysis. A safety hazard can be described as the probability of an undesirable event with the magnitude of foreseeable consequences. Foreseeable consequences may include damage to equipment or reputation, loss of money, injury to patients or personnel, etc. The seriousness of these consequences may range from negligible to catastrophic.

## 2.0 Scope of Document

We'll first provide a table listing failure mode probabilities and then a table listing a hazard's possible severity. Then we'll identify possible failure modes and list their probability, severity level and how they can be mitigated.

## 3.0 Reference Documents

To support this failure modes and effects analysis, the following reference documents should provide a better understanding of PBTS configuration management software and the safety aspects of the configuration system.

- PBTS Configuration Management System Software Requirements Specification, Document #3001447
- PBTS Configuration Management System High Level Design, Document #3001486

## 4.0 Developing the Failure Modes and Effects Catalog

This catalog is a qualitative form of analysis that denotes possible failure modes associated with the PBTS. The catalog contains the following elements:

- Identification of failure modes and their associated root causes
- Evaluates the effects of each failure mode towards patients and operating personnel
- Determines the probability of occurrence level for each failure mode
- Categorizes each failure mode in regards to level of severity.

Failure modes are categorized by functional area. Some failure modes are common in the software regardless of functional area and shall be listed first. These are generally memory allocation failures, out of tolerance conditions, etc.

## 5.0 Occurrence Levels and Severity Categories

Each of the failure modes was evaluated for probability of occurrence levels and severity categories. This evaluation process is summarized in the below.

| Level | Failure Mode Probability Of Occurrence | Failure Mode Occurrence Description |
|---|---|---|
| A | Frequent | Often experienced or likely to occur |
| B | Moderate | Several times experienced or occurring |
| C | Occasional | Sometimes experienced or occurring |
| D | Remote | May be experienced or may occur |
| E | Unlikely | Unlikely to be experienced or to occur |
| F | Impossible | Practically impossible |

| Category | Hazard Severity | Failure Mode Effect Description |
|---|---|---|
| I | Catastrophic | Causes death, total disability, loss of company image, detrimental financial loss, system loss |
| II | Critical | Causes severe injury with partial disability, severe loss of image, large financial loss, partial system loss |
| III | Marginal | Causes injury, transient loss of image, indirect financial loss, system damage |
| IV | Negligible | Causes minor injury, minor image or financial loss, minor system damage |

Many of the failure modes may come from base classes and support classes whose failure modes have already been identified in the PBTS Software Failure Modes and Effects Analysis. They will not be re-stated here.

Failures caused by operating system or miscellaneous programming errors

| Failure Mode | Cause | Level | Effect | Cat. | Mitigation | Revised Level/Cat |
|---|---|---|---|---|---|---|
| memory allocation failed | memory full | E | inability to proceed | IV | - garbage collection<br>- smart memory allocation schemes for Message, ByteString classes | |
| memory allocation failed | memory fragmentation | A | inability to proceed | IV | regular system maintenance | E/IV |
| file system error | OS | D | system halts | II | code review, code test | E/IV |
| division by 0 | programming error | D | math exception | III | code review, test | E/IV |
| memory leaks | programming error | C | segmentation fault | IV | code review, test | E/IV |
| system sluggish | exhaustive error detection/ correction | B | thrashing | III | limit error checking to critical errors only. focus on recovery (vs. correction) | D/III |
| | | | | | | |

Failure modes caused by user error

| Failure Mode | Cause | Level | Effect | Cat. | Mitigation | Revised Level/Cat |
|---|---|---|---|---|---|---|
| tolerance values are incorrect | user enters incorrect tolerances | C | possible hazardous system state<br>wrong dose delivered<br><br>hardware tolerances exceeded | II | protocol with checks for changing configurations; compare configuration values against hardwired hardware limits | D/III |
| values specified are out of tolerance | user specifies out of tolerance value | B | possible injury to patient and or personnel<br><br>possible damage to equipment | II | software will compare all values with baseline to ensure tolerances are met | E/IV |
| invalid data is not trapped | user enters invalid data | B | application locks up or seg fault detected | III | trap invalid data and inform user | E/IV |

Database Failure Modes

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | |

| Failure Mode | Cause | Level | Effect | Cat. | Mitigation | Revised Level/Cat |
|---|---|---|---|---|---|---|
| Database Server crashes | network problem<br><br>internal error, server stops responding | B | treatment and tuning delayed until back online | II | Do not rely on database for retrieval; provide file system storage where processes will retrieve configuration data | E/IV |
| Client cannot connect to database server | network error | C | treatment and tuning delayed | III | Do not rely on database for retrieval; provide file system storage where processor will retrieve configuration data | E/IV |
| Database is corrupted | server crashed during an update to data | C | user changes not saved<br><br>data may not be reliable | III | maintain backup of database at least to last saved configuration | E/IV |
| Failure to updated field | field is in more than one location | B | may treat with outdated information | II | normalize database | E/IV |

Failure Modes when generating files

| Failure Mode | Cause | Level | Effect | Cat. | Mitigation | Revised Level/Cat |
|---|---|---|---|---|---|---|
| Database and Reports are out of sync | Report was never generated | C | treatments proceed with possibly outdated configurations | III | compare data and time stamp of database and file | E/IV |
| Generated report is corrupted | Not all data was written to file(s) | C | treatment and tuning delayed | II | checksum verifying files against database | E/IV |
| Report not generated | No space left on device | D | treatment may be delayed | II | Hard drives that exceed our memory needs | E/IV |
| NFS Error while generating report | Network error | D | treatment may be delayed | II | | |

## 6.0 Failure Mode Mitigation

The mitigation process evaluates the failure modes and effects and establishes a form of corrective action to reduce their risk. Both acceptable and unacceptable failure modes are mitigated to ensure a safer system.

## 7.0 Summary

The primary purpose of the failure modes and effects analysis is to determine the failure modes and reduce their associated risks as much as possible. Using system requirements and software architecture, the failure modes of each functional area, as well as the system as a whole, can be identified. This failure modes and effects analysis is then used during detail design to insure mitigation is included in the design and implementation.

# APPENDIX B

Doc # 2001779
Rev:B

# A,B,C type power supply analysis

Used for "tuning" an instance of an ABC type power supply.

This is a Mathcad generated document.

File: Vert. Trim
Supply type: A
Magnet type: Sextupole magnet.
Date: 5/17/00

Author: Greg Jenkins and Darrin Taylor

Optivus Technology, Inc.

# A,B,C type power supply analysis

The INVERPOWER supplies used in the accelerator are 40 Khz switching supplies. These supplies use multiple converter banks in parallel to provide the total power. Each bank is a seperate two transistor "Buck" type forward converter. The supplies use current mode feedback in the inner loop and voltage and current feedback in the outer loops. This MathCad document will provide an analysis to tune the feedback loops for a particular type and instance of supply. This analysis assumes that all modifications have been made to the MPI board to allow true current mode feedback and fix other problems uncovered during this investagation (see related documents). The design criteria for the compensators also assumes inductive loads. For a particular type of supply and magnet, update all varables and identify file, supply, magnet and date on cover sheet and the modification report page at the end of this document. The modification report can then be used for updating the supply.

Power supply parameters

| | | |
|---|---|---|
| Max Current output | $I_m := 200$ | |
| Max Voltage output | $V_m := 10$ | |
| Control voltage range | $V_c := 10$ | |

Filter and load model

| | | |
|---|---|---|
| Load resistance and inductance | $R_o := 35.7 \cdot m\Omega$ | $L_o := 1.6 \cdot mh$ |
| Filter inductor resistance and inductance | $R_f := 5 \cdot m\Omega$ | $L_f := 70 \cdot uh$ |
| Filter capacitor resistance and capacitance | $R_{esr} := 20 \cdot m\Omega$ | $C_f := 6100 \cdot uf$ |
| Input line filter inductance and capacitance | $L_i := 1 \cdot mh$ | $C_i := 3600 \cdot uf$ |

Note: Type A supply has Cf=6100uf and B & C supply Cf=2000uf
Type A & B Li=1mh and Ci=3600uf.
Type C supply Li=1.3mh and Ci=10800uf

Transformer model

| | |
|---|---|
| Transformer and line primary circuit resistance | $R_p := 1.8 \cdot \Omega$ |
| Current transformation ratio | $N_i := \frac{20}{3}$ |
| Reflected impedance transformation ratio | $N_z := N_i^2$ |

Converter model

Note: Type A supply is Ni=20/3 and B & C supply Ni=16/3

| | | |
|---|---|---|
| Load impedance and admitance | $Z_o(s) := R_o + s \cdot L_o$ | $Y_o(s) := \frac{1}{Z_o(s)}$ |
| Filter capacitor impedance and admitance | $Z_c(s) := R_{esr} + \frac{1}{s \cdot C_f}$ | $Y_c(s) := \frac{1}{Z_c(s)}$ |
| Load and capacitor in parallel | $Y_{co}(s) := Y_c(s) + Y_o(s)$ | $Z_{co}(s) := \frac{1}{Y_{co}(s)}$ |
| Filter inductor impedance | $Z_l(s) := R_f + s \cdot L_f$ | |
| Total secondary impedance | $Z_s(s) := Z_{co}(s) + Z_l(s)$ | |
| Reflected primary impedance | $Z_p(s) := Z_s(s) \cdot N_z$ | |
| Total primary impedance and admitance | $Z_t(s) := R_p + Z_p(s)$ | $Y_t(s) := \frac{1}{Z_t(s)}$ |

# Inner current loop foward path

<u>Pulse width modulator</u>

The PWM gain is determined by the peak to peak amplitude of the clock signal at the comparitor inside the UC3846 chip. Measured at pin 1 of IC46:

$ck_{pp} := 1.76 \cdot volts$

The clock is divided down by the following resisters: $R182 := 470 \cdot \Omega$ $R181 := 1 \cdot k\Omega$ $R147 := 390$

The divide ratio is:

$$d_{ck} := \frac{1}{R182 \cdot \left(\frac{1}{R181} + \frac{1}{R147}\right) + 1}$$

If both outputs of the UC3846 chip are used this creates full frequency (35 to 45 Khz) alternate bank firing at maximum duty cycle (80 to 90%). If only one output is used then only half frequency simultaneous firing can occure with reduced gain at half the maximum duty cycle. Check wiring of supply and set b=1 for both or b=2 for one output uNote: A supply is b=2 and B & C supply is b=1

$b := 2$

The maximum duty cycle depends on the duty cycle of the clock signal. Measure the rise time (ton) and the fall time (toff) (See "Oscillator analysis" at end of this document to calculate these values)

$t_{on} := 22.52 \cdot us$

$t_{off} := 4.41 \cdot us$

The clock frequency and maximum duty cycle are:

$$t_{ck} := t_{on} + t_{off} \qquad f_{ck} := \frac{1}{t_{ck}} \qquad dc_{max} := \frac{t_{on}}{t_{on} + t_{off}}$$

$f_{ck} = 37.133 \cdot khz$

$dc_{max} = 0.836$

The PWM chip has an amplifier with a gain of 3 that both clock and feedback pass through:

$K_{pwm} := 3$

Taking into account the 3X gain, the final gain with duty cycle limiting is:

$$G_{pwm} := \left(\frac{1}{ck_{pp} \cdot d_{ck} \cdot K_{pwm}}\right) \cdot \left(\frac{dc_{max}}{b}\right)$$

$G_{pwm} = 0.212$

<u>Sampling</u>

The sampling period and frequency is:

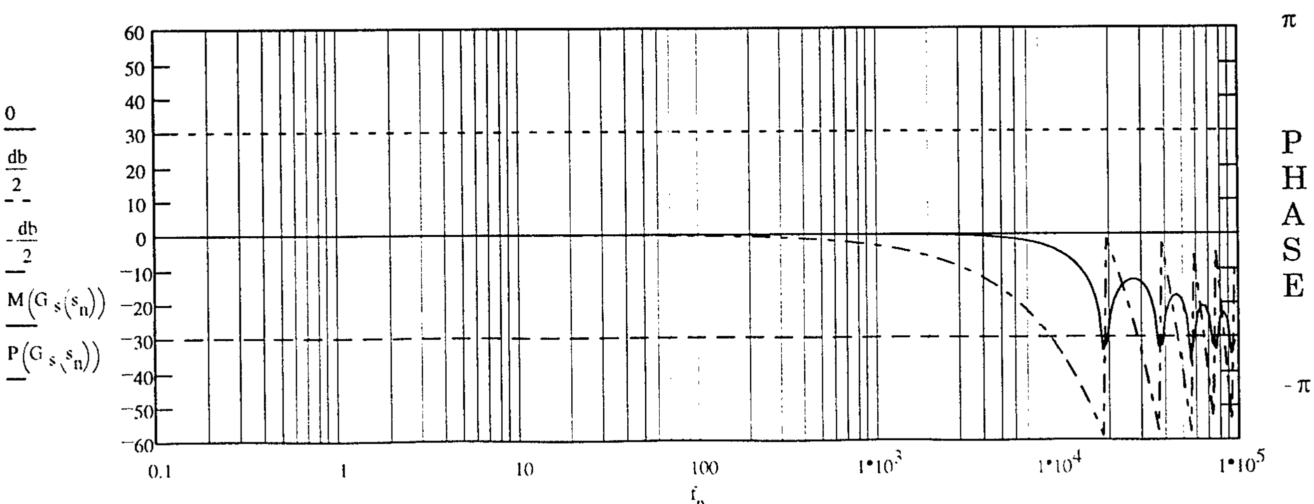
$$t_s := t_{ck} \cdot b \qquad f_s := \frac{1}{t_s}$$

$f_s = 18.567 \cdot khz$

The sampling effect is modeled with the following transfer function:
(The main significance is the phase lag the sampling contributes to the loop)

$$G_s(s) := \frac{1 - e^{-t_s \cdot s}}{t_s \cdot s}$$

Sampler transfer function



# Inner current loop foward path

Input line

The power supply input is a 3 phase source that is full wave (peak) rectified and filtered. Line to neutral is 120 volts rms making 208 volts rms line to line. This is modeled as a gain that is pulse width modulated.

Line: $G_{line} := 120\cdot\sqrt{3}\cdot volts$ Three phase peak rectifier (gain): $G_{peak} := \sqrt{2}$

DC voltage to the converters is: $G_{line}\cdot G_{peak} = 293.939 \cdot volts$

The input line filter transfer function is: $Z_i(s) := s\cdot L_i + R_p$ $Y_i(s) := s\cdot C_i + \frac{1}{Z_p(s)}$

Foward path gain $G_l(s) := \frac{1}{Z_i(s)\cdot Y_i(s) + 1}$

The following fudge factor was created to match the model with masurments made on a power supply. This variation is attributed to energy storage and loss in the primary and secondary snubber circuits, transformer and inductor core losses and parasatics affecting the inner loop foward path (converter) gain.

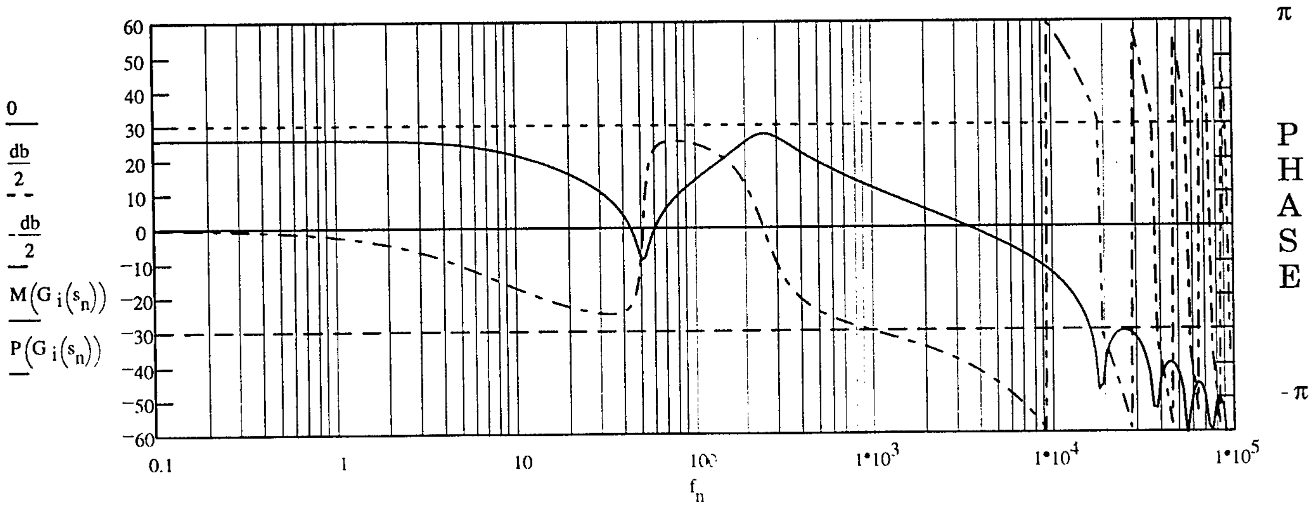
ff = Fudge factor $Gi_{ff} := 1.13$

The output is a current converted from a modulated voltage by the total primary addmitance of the converter. Total inner loop foward path gain is: $G_i(s) := G_{pwm}\cdot G_s(s)\cdot Gi_{ff}\cdot G_{line}\cdot G_{peak}\cdot Y_t(s)$

**Open loop** DC voltage to current gain from pin 7 of PWM chip to primary current is: $|G_i(.001i)| = 19.497$

In DBs: $M(G_i(.001i)) = 25.799 \cdot DB$

Inner loop foward path Transfer function



# Inner current loop feedback path

Primary current sensor

The output transformer prymary current is fed back from a 200:1 current sense transformer with a turns ratio of: $N_s := \frac{1}{200}$

This current is transformed to a voltage by the impedence of two 4.7 ohm resistors in series creating a current sense resistance of 9.4 ohms $R_s := 2 \cdot 4.7 \cdot \Omega$

Feedback gain factor Ki

There is a current transformer for each bank in a particular supply. These are unity gain buffered with differental input op-amps and summed togather at IC40. The gain Ki of IC40 is set by resistor R160 so Ki = R160/R163 with R163 fixed: $R163 := 1 \cdot k\Omega$

R160 is used to set the feedback path gain and therefore establishes the **closed loop gain** from pin 7 of the PWM chip to the primary of the output transformer. A 3 volt range at pin 7 should correspond with the max current out as transfromed from primary to secondary. This current is either load limited by the max voltage or current limited by the max current of the supply.

Max current with this load is: $\frac{V_m}{R_o} = 280.112 \cdot \text{amps}$

Limit to: $I_m = 200 \cdot \text{amps}$ Secondary current or: $I_m \cdot \frac{1}{N_i} = 30 \cdot \text{amps}$ Primary current

Therefore the closed loop gain should be equal or greater than: $G_{icx} := \frac{I_m}{3 \cdot \text{volts}} \cdot \frac{1}{N_i}$ $G_{icx} = 10$

(R160 will be calculated below to extablish this gain)

Current feedback voltage divider and gain

The feedback current is voltage divided by the same resistors as the clock divider with a divide ratio of:

$$d_i := \left[ \frac{1}{R181 \cdot \left( \frac{1}{R182} - \frac{1}{R147} \right) + 1} \right]$$

Feedback path gain

Again a feedback path fudge factor was needed to match the model with the supply. We do not have a good excuse for this other than both factors were needed. $Hi_{ff} := 1.11$

Closed loop DC gain

R160 can now be calculated to establish the desired closed loop gain Gicx. Define Gix as the foward path gain at DC with a 10% low line condition:

$$G_{ix} = |G_i(.001 \cdot i)| \cdot 0.9$$

Then the gain of IC40 must be: $K_i := \frac{G_{ix} - G_{icx}}{N_s \cdot R_s \cdot d_i \cdot K_{pwm} \cdot Hi_{ff} \cdot G_{icx} \cdot G_{ix}}$ $K_i = 1.564$

Therefore calculate R160: $R160 := K_i \cdot R163$ $R160 = 1.564 \cdot k\Omega$ $R160 := 1.6 \cdot k\Omega$ $K_i := \frac{R160}{R163}$

and select standard value.

By superposition the feedback passes through the 3X gain (Kpwm) amplifier inside the chip also. The total inner current loop feedback path gain is:

$$H_i(s) = N_s \cdot R_s \cdot K_i \cdot d_i \cdot K_{pwm} \cdot Hi_{ff}$$

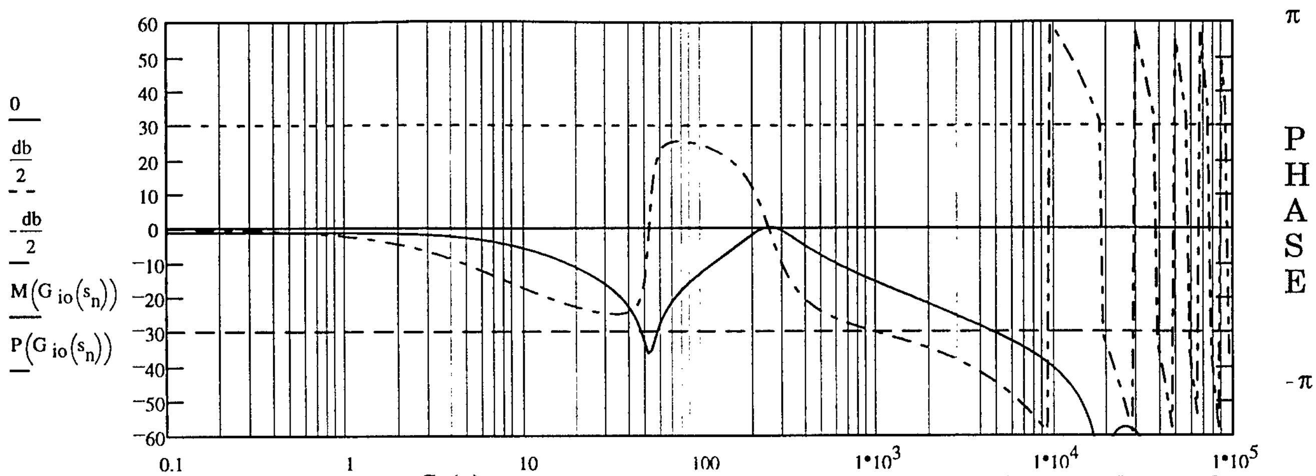
At low line voltage define: $G_{ix}(s) := G_i(s) \cdot .9$ The closed loop gain is then: $G_{ic}(s) := \frac{G_{ix}(s)}{1 + G_{ix}(s) \cdot H_i(s)}$

Therefore the low frequency closed loop gain at low line voltage then meets the requirements stated above: $G_{ic}(.001i) = 9.903$

In DBs: $M(G_{ic}(.001i)) = 19.915 \cdot DB$

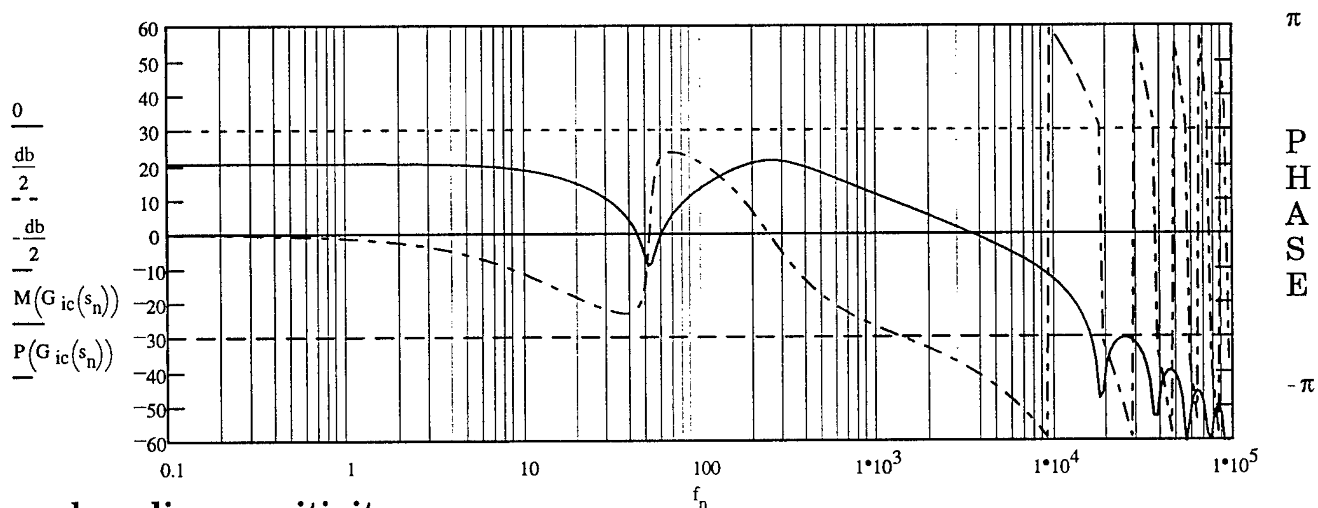
# Inner current loop transfer functions

**Inner loop open** $G_{io}(s) := G_i(s) \cdot H_i(s)$




**Inner loop closed** $G_{ic}(s) := \dfrac{G_i(s)}{1 + G_{io}(s)}$

At low frequency and nominal line voltage the gain is: $|G_{ic}(.001i)| = 10.495$ In DBs: $M(G_{ic}(.001i)) = 20.419 \cdot DB$

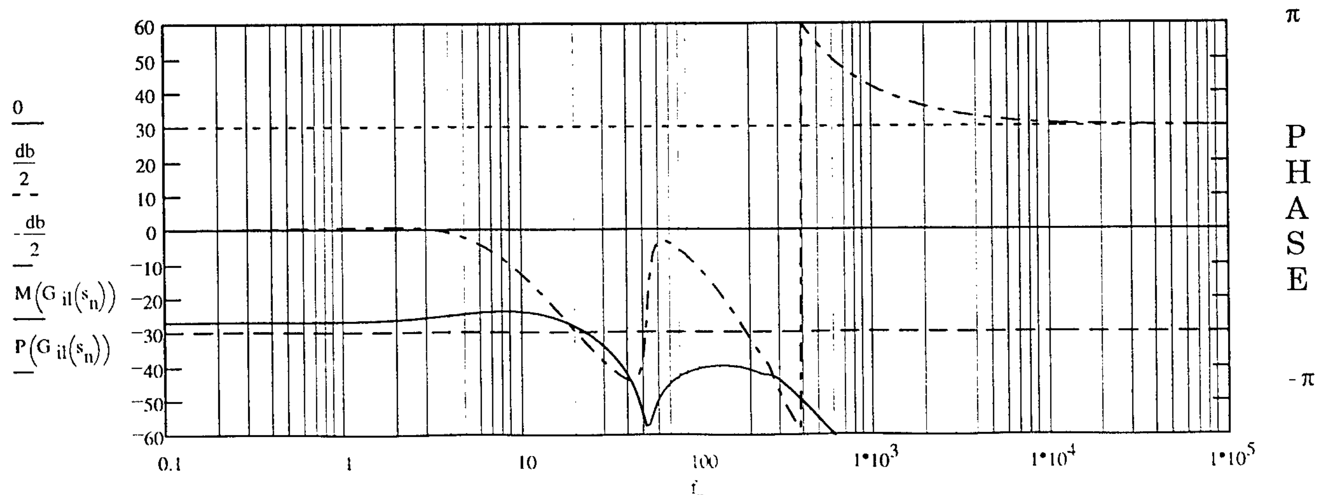



**Inner loop line sensitivity**

This is the gain at full output voltage from the 208 volt line to primary current, showing sensitivity (volts to amps) to line varations:

$$G_{il}(s) := \frac{G_l(s) \cdot G_{peak} \cdot Y_t(s)}{1 + G_{io}(s)} \cdot \frac{dc_{max}}{b}$$

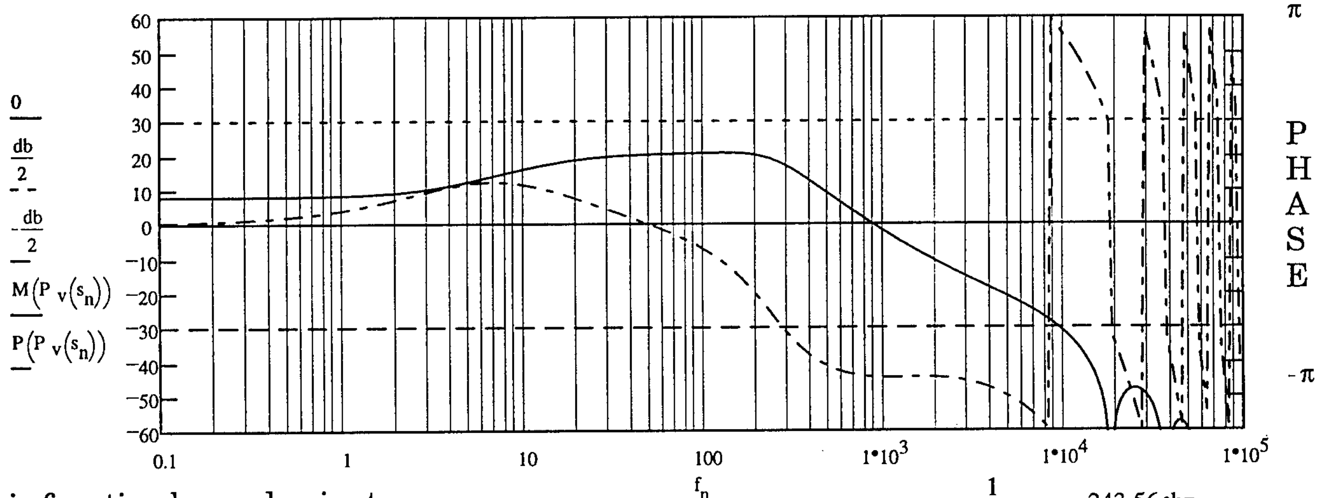
@DC $|G_{il}(.001i)| = 0.044$ In DBs: $M(G_{il}(.001i)) = -27.09 \cdot DB$



# Voltage loop foward path

Voltage loop "plant"

To design the compensator it is usefull to look at the "plant" to be compensated. In this case the plant is made up of the inner closed loop function, The current transformation ratio of the transformer, and the current to voltage transformation impeadance of the filter capacitor and load in parallel.
Plant transfer function: $P_v(s) := G_{ic}(s) \cdot N_i \cdot Z_{co}(s)$




This function has a dominate pole at: (aproximated) $\frac{1}{2\cdot\pi\cdot\sqrt{L_f C_f}} = 243.56 \cdot hz$

This pole will be used to set the zero of the compensator.

Observation only: there is a pole/zero cancellation by the product of Gic and Zco at (again only aproximated): $\frac{1}{2\cdot\pi\cdot\sqrt{L_o \cdot C_f}} = 50.944 \cdot hz$

Compensator design

The function of the compensator is to provied high loop gain at low frequencies to reduce static error and provide a zero to help cancel the Lf, Cf pole shown above. A pole will be placed above the zero to attinuate high frequency noise.

Select R210 for the required open loop gain for crossover at 90 degrees phase margin and C108 for both convenience and reasonable R247 value:

(Note: R148=R149=R151=R210)
( & C109=C108 & R248=R247) $R210 := 20 \cdot k\Omega$ $C108 := 1.0 \cdot uf$

R247 will be calculated to cancel the Lf, Cf pole in the plant: $R247 := \frac{1}{C108}\cdot\sqrt{L_f C_f}$ $R247 = 0.653 \cdot k\Omega$
Select standard value: $R247 := 0.665 \cdot k\Omega$

C67 will be calculated to be some factor above the zero: (factor not critical but C68 = C67 must hold) $C67 := \frac{C108}{10}$ $C67 = 100 \cdot nf$ $C67 := 100 \cdot nf$

The resulting transfer function of the compensator is:

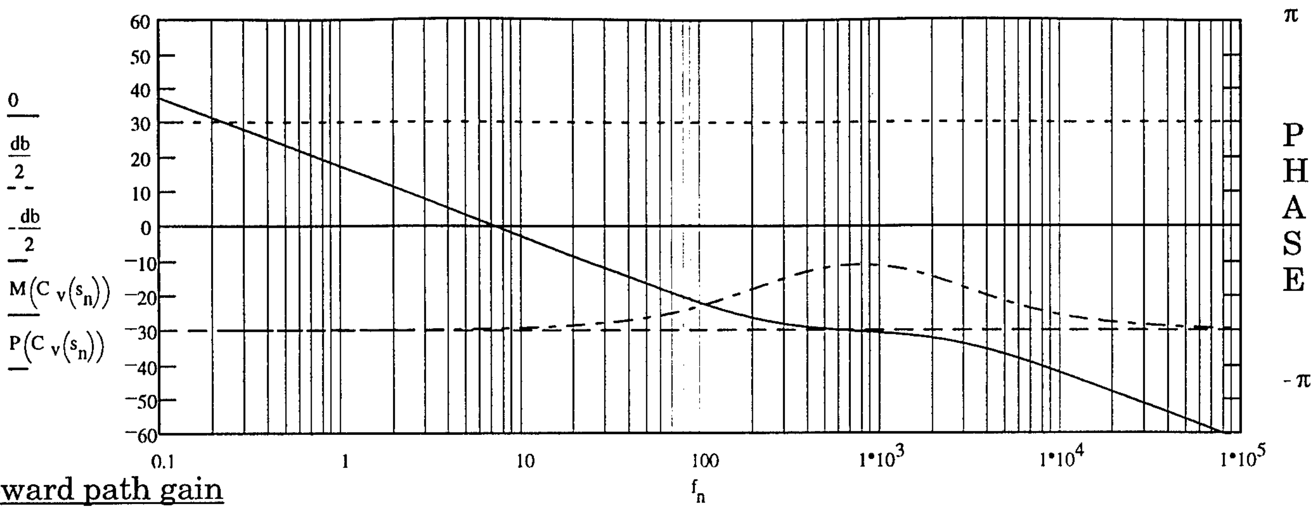
$$C_v(s) := \frac{1}{\left(s\cdot C67 + \frac{1}{R247 + \frac{1}{s\cdot C108}}\right)\cdot R210}$$

The zero and pole frequency of this function is: $\frac{1}{2\cdot\pi\cdot C108\cdot R247} = 239.331 \cdot hz$ $\frac{C67 + C108}{2\cdot\pi\cdot C67\cdot C108\cdot R247} = 2.633 \cdot khz$

The "flat portion" gain is: $\frac{R247}{R210} = 0.033$ In DBs: $M\left(\frac{R247}{R210}\right) = -29.564 \cdot DB$

# Voltage loop foward path

## Compensator transfer function



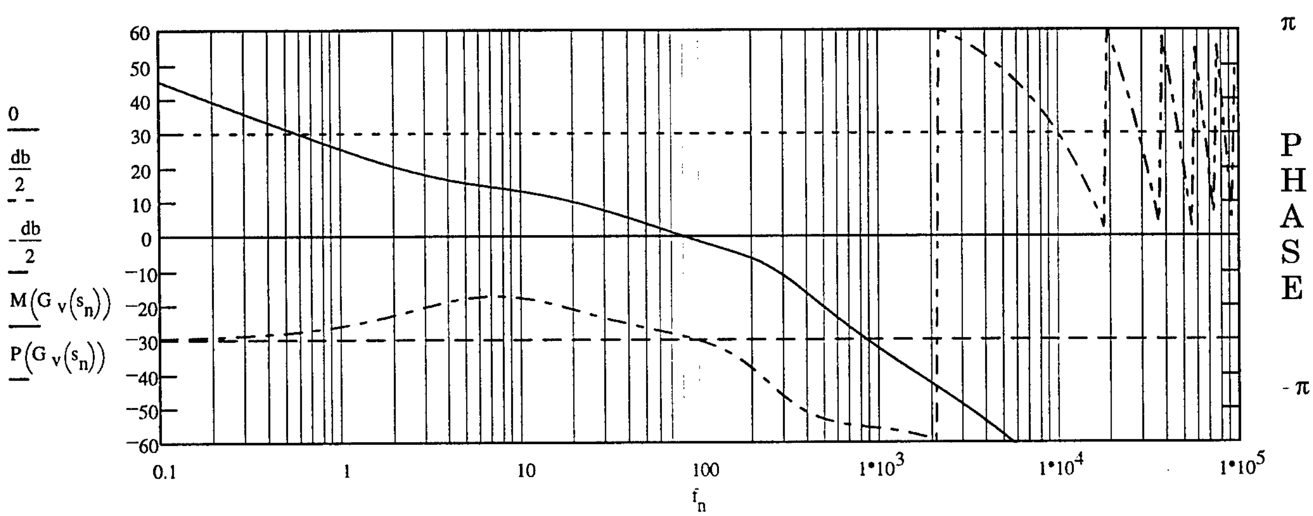

## Foward path gain

The total foward path consist of the compensator, inner loop (closed), transformer current transformation ratio, and a current to voltage transformation impeadance consisting of the filter capacitor and load (ie the plant as described above).

$$G_V(s) := C_V(s) \cdot G_{ic}(s) \cdot N_i \cdot Z_{co}(s)$$

Or: $$G_V(s) := C_V(s) \cdot P_V(s)$$

## Voltage loop foward path transfer function




## Feedback path gain

At low frequencies the foward path gain is high so the feedback path gain sets the closed loop gain. In this case its a constant set by the control voltage to maximum ouput voltage ratio.

$$K_V := \frac{V_c}{V_m}$$

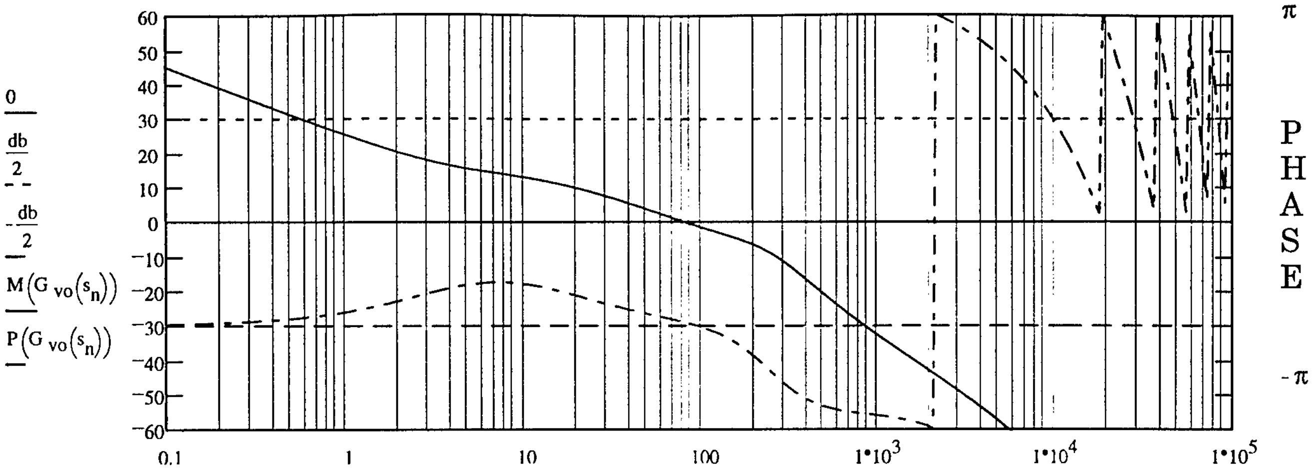
Feedback gain is: $K_V = 1$

Closed loop gain is then: $\frac{1}{K_V} = 1$

# Voltage loop transfer functions

**Voltage loop open**

$$G_{vo}(s) := G_v(s)\cdot K_v$$

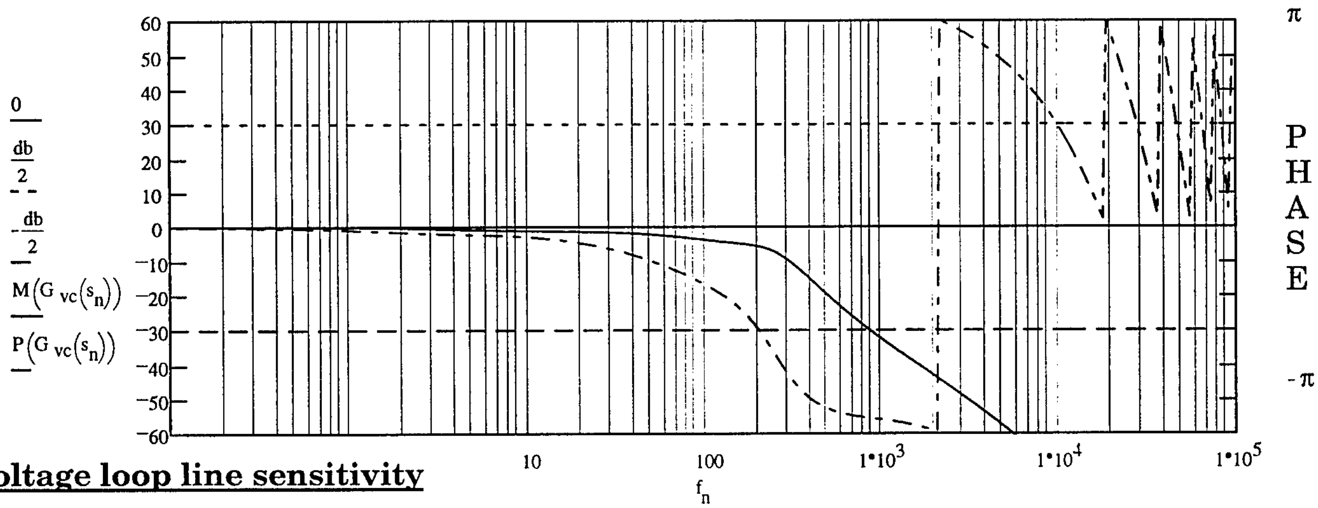



Note: This is the Bandwidth to limit ripple current to 10 amps RMS in the output filter capacitor at full output voltage. A higher bandwidth may be desireable:

$$\frac{10\cdot amps}{2\cdot\pi\cdot V_m\cdot volts\cdot C_f}\cdot\sqrt{2} = 36.898\cdot hz$$

**Voltage loop closed**

$$G_{vc}(s) := \frac{G_v(s)}{1+G_{vo}(s)} \qquad \left|G_{vc}(i\cdot .001)\right| = 1$$




**Voltage loop line sensitivity**

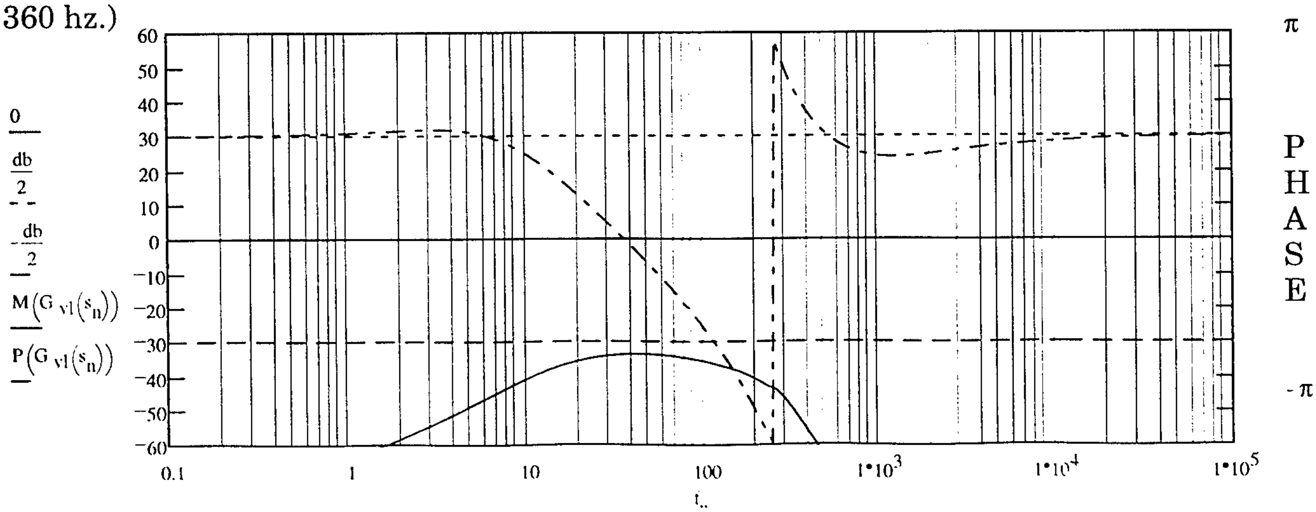
From the 208 volt line to output

$$G_{vl}(s) := G_{il}(s)\cdot\frac{N_i\cdot Z_{co}(s)}{1+G_{vo}(s)}$$

@360hz $\left|G_{vl}(2\cdot\pi\cdot 360\cdot i)\right| = 2.31\cdot 10^{-3}$

In DBs: $M\left(G_{vl}(2\cdot\pi\cdot 360\cdot i)\right) = -52.726\cdot DB$

(DC rejection is >100db but three phase ripple will occure at 360 hz.)

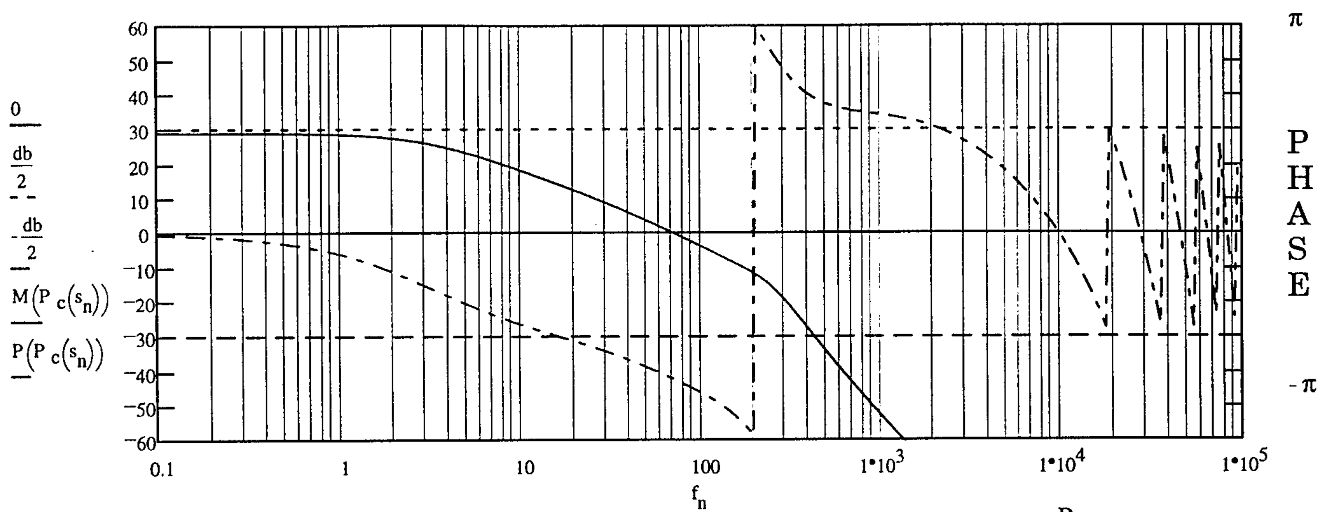


# Current loop foward path

## Current loop "plant"

Again to design the compensator it is usefull to look at the "plant" to be compensated. In this case the plant is made up of the voltage closed loop function and the voltage to current transformation admittance of the load.

Plant transfer function: $P_c(s) := G_{vc}(s) \cdot Y_o(s)$




A pole due to the resistance Ro and inductance Lo of the load is at: $\frac{R_o}{L_o \cdot 2 \cdot \pi} = 3.551 \cdot hz$

This pole can be canceled by the zero of the compensator.

## Compensator design

The function of the compensator is to provied high loop gain at low frequencies to reduce static error and provide a zero to help cancel the Ro, Lo pole shown above. A pole will be placed above the zero to attinuate high frequency noise.

Select R222 for the required open loop gain for crossover at 90 degrees phase margin and C107 for both convenience and reasonable value of R246:

(Note: R196 = R222) $R222 := 20 \cdot k\Omega$ $C107 := 1 \cdot uf$

R203 will be calculated to cancel the Ro, Lo pole in the plant: $R246 := \frac{L_o}{C107 \cdot R_o}$ $R246 = 44.818 \cdot k\Omega$ $R246 := 44.2 \cdot k\Omega$

C93 will be calculated to be some factor above the zero: (not critical) $C93 := \frac{C107}{10}$ $C93 = 100 \cdot nf$ $C93 := 100 \cdot nf$

The resulting transfer function of the compensator is:

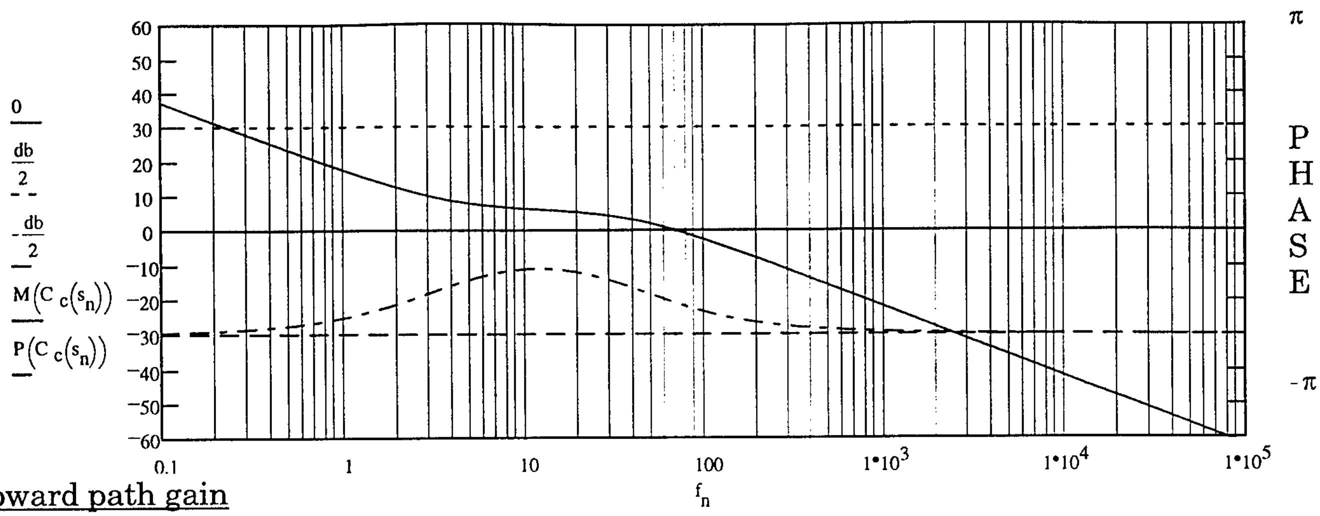
$$C_c(s) := \frac{1}{\left(s \cdot C93 + \frac{1}{R246 + \frac{1}{s \cdot C107}}\right) \cdot R222}$$

The zero and pole frequency of this function is: $\frac{1}{2 \cdot \pi \cdot C107 \cdot R246} = 3.601 \cdot hz$ $\frac{C93 + C107}{2 \cdot \pi \cdot C93 \cdot C107 \cdot R246} = 39.609 \cdot hz$

The "flat portion" gain is: $\frac{R246}{R222} = 2.21$ In DBs: $M\left(\frac{R246}{R222}\right) = 6.888 \cdot DB$

# Current loop foward path

## Compensator transfer function



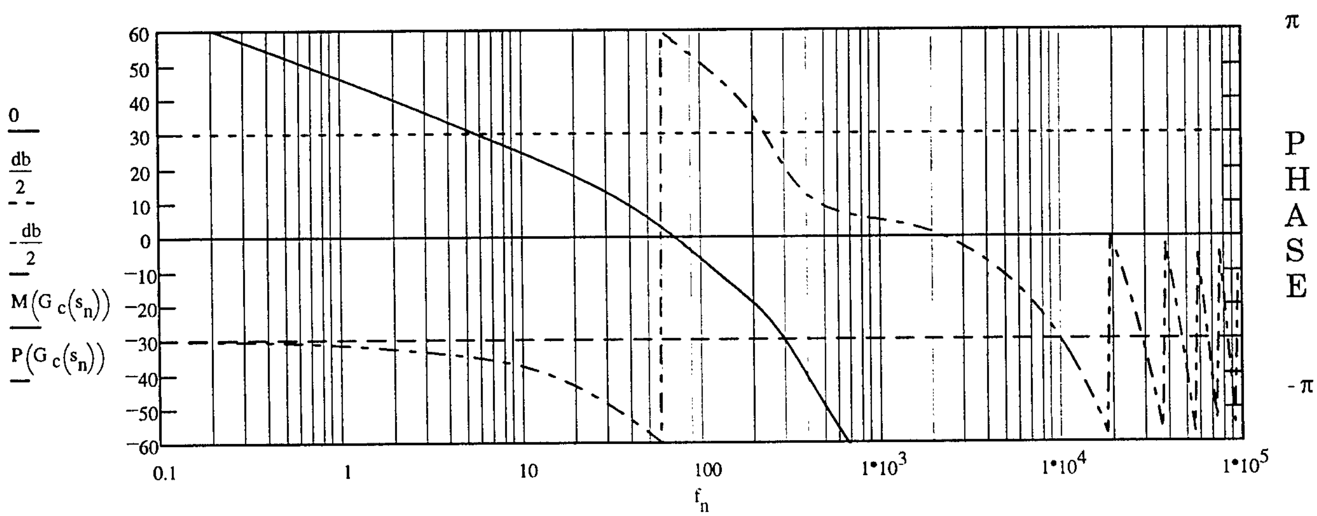

Foward path gain

The total foward path consist of the compensator, voltage loop (closed) and the voltage to current transformation admitance of the load (ie the plant as described above).

$$G_c(s) := C_c(s) \cdot G_{vc}(s) \cdot Y_o(s)$$

Or: $$G_c(s) := C_c(s) \cdot P_c(s)$$

## Current loop foward path transfer function




Feedback path gain

At low frequencies the foward path gain is high so the feedback path gain sets the closed loop gain. In this case its a constant set by the control voltage to maximum ouput current ratio.

$$K_c := \frac{V_c}{I_m}$$

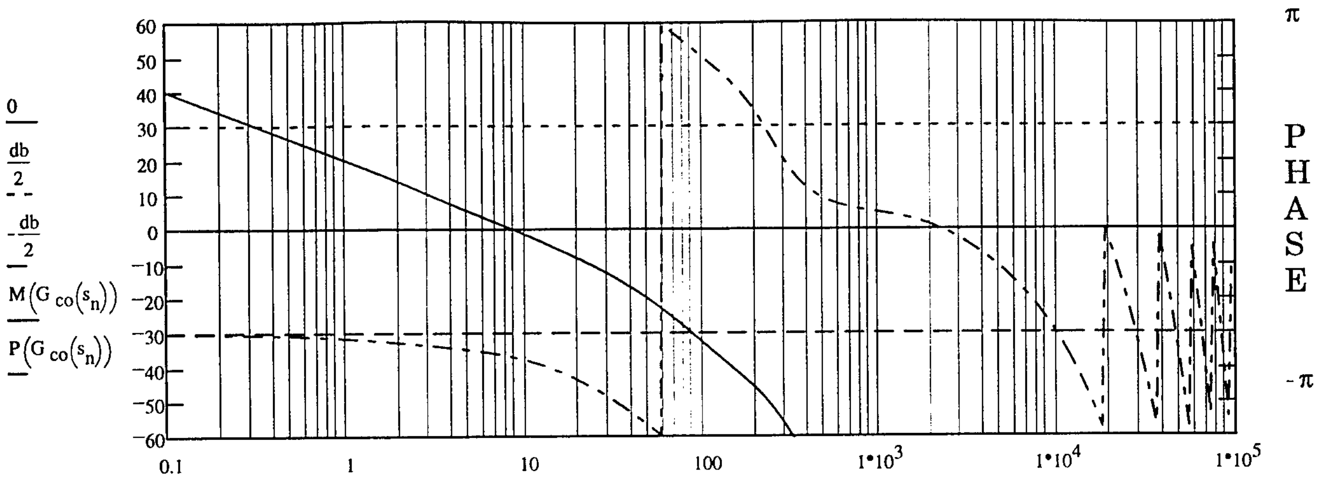
Feedback gain is: $K_c = 0.05$

Closed loop gain is then: $\frac{1}{K_c} = 20$

# Current loop transfer functions

## Current loop open

$$G_{co}(s) := G_c(s)\cdot K_c$$

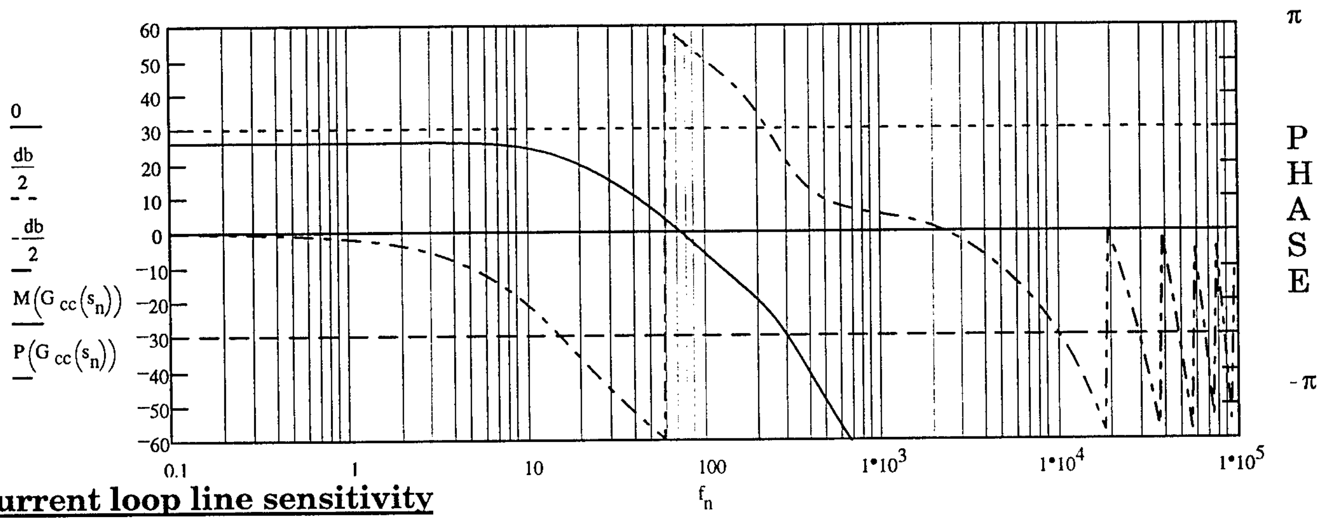



## Current loop closed

$$G_{cc}(s) := \frac{G_c(s)^{f_n}}{1+G_{co}(s)}$$

DC gain: $\left|G_{cc}(i\cdot .001)\right| = 20$

In DBs: $M(G_{cc}(.001\cdot i)) = 26.021\cdot DB$




## Current loop line sensitivity

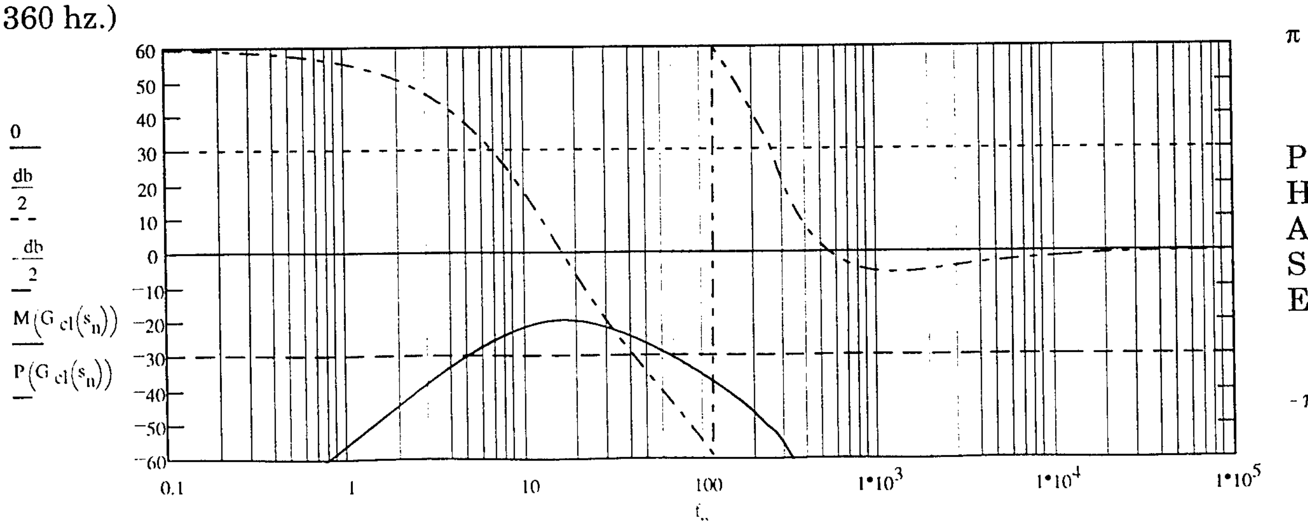
From the 208 volt line to output

(DC rejection is >100db but three phase ripple will occure at 360 hz.)

$$G_{cl}(s) := G_{vl}(s)\cdot\frac{Y_o(s)}{1+G_{co}(s)}$$

@360hz $\left|G_{cl}(2\cdot\pi\cdot 360\cdot i)\right| = 6.381\cdot 10^{-4}$

In DBs: $M(G_{cl}(2\cdot\pi\cdot 360\cdot i)) = -63.903\cdot DB$



# Stability plots

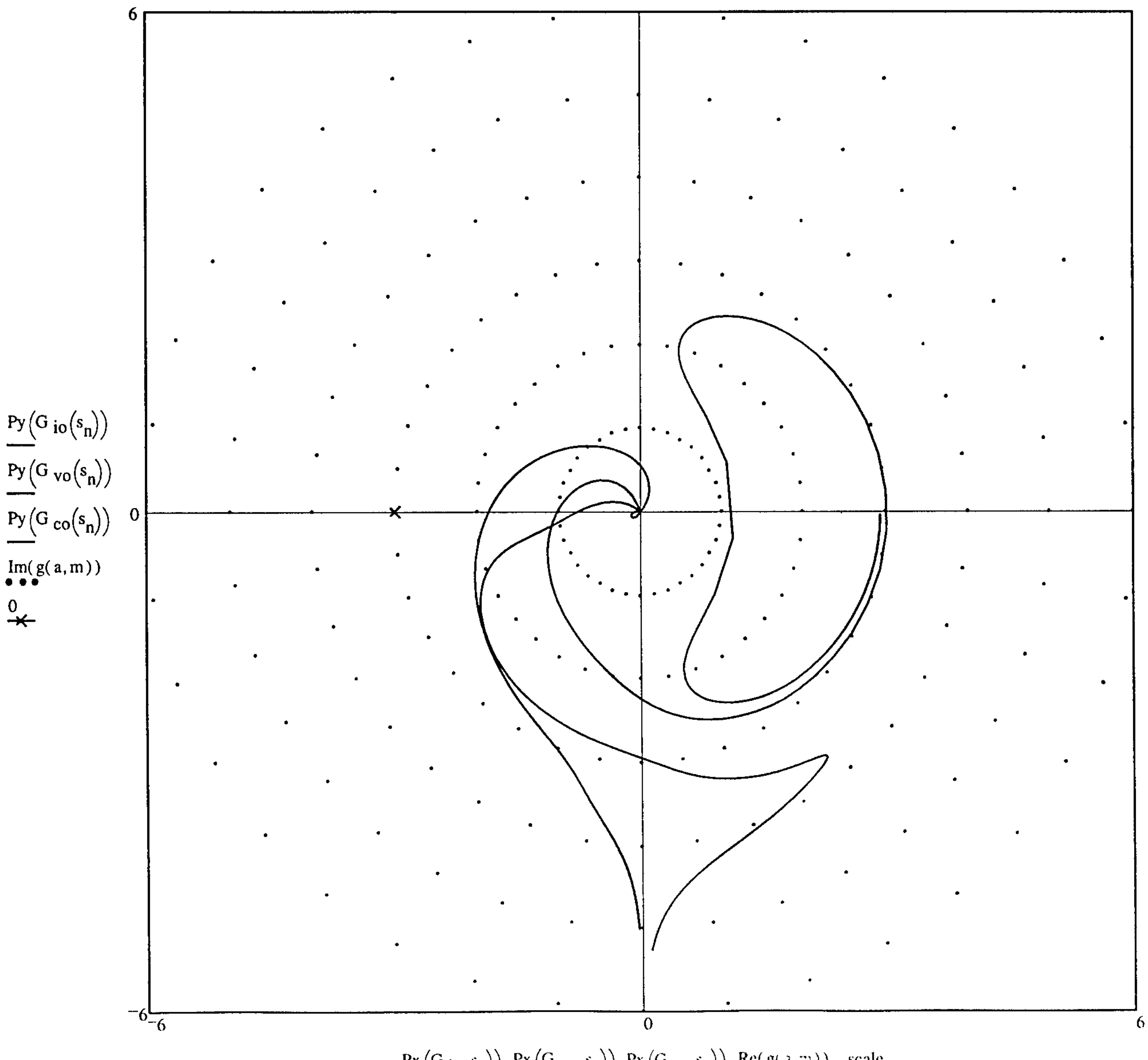
Time domain analysis showed that 90 degree phase margins gave good step response so stability should be good. Here is the Nyquist plots for all three loops for a quick check.

**Nyquist chart**

$\text{scale} := \text{ceil}\left(\frac{\text{db}}{20}\right)$ $\quad Py(x) := \text{if}\left(|x| > 10^{-\text{scale}}, \log\left(|x| \cdot 10^{\text{scale}}\right), 10^{-\text{scale}}\right) \cdot \sin(\arg(x))$ $\quad m := 0..\text{scale} \cdot 2$ $\quad a := 0, \frac{2 \cdot \pi}{36} .. 2 \cdot \pi$

$Px(x) := \text{if}\left(|x| > 10^{-\text{scale}}, \log\left(|x| \cdot 10^{\text{scale}}\right), 10^{-\text{scale}}\right) \cdot \cos(\arg(x))$ $\quad g(a, m) := e^{i \cdot a} \cdot m$

This is a polor plot of the open loop gains of each feedback loop. Unlike most Nyquist plots the magnitude scale on this plot is logrithmic with each circle representing 20 DBs (x10) or one log cycle. The -1 gain point (0 DBs @ 180 degrees) is marked with an X. If any feedback loop gain line encircles this point the loop will be unstable. The points of the magnitude scale (circles) are 10 degrees apart so the phase margin can be estimated by the nimber of degrees between the -1 mark (X) and where the open loop gain line crosses the -1 gain circle. The gain margin is the magnitude of the distance between the -1 mark and where the gain line crosses the horizontal axis on the negitive side.



# Over current shutdown

The PWM chip (UC3846) has an over current shut down input (SD) on pin 16. At a voltage of 350mv on this pin the chip will cut off the pulse outputs. IC40 pin 6 is connected to pin 16 through a voltage divider with a divide ratio, including internal 6K resistor, of:

$$R165 := 20 \cdot k\Omega \qquad R220 := 6.19 \cdot k\Omega \qquad d_{sd} := \frac{1}{R165 \cdot \left(\frac{1}{R220} + \frac{1}{6 \cdot k\Omega}\right)}$$

Working backwards around the loop, shut down will occure at a total transformer primary current (the sum of all banks firing simultaneously) of:

$$I_{sdp} := (350 \cdot mv) \cdot \frac{1}{d_{sd}} \cdot \frac{1}{N_s \cdot R_s \cdot K_i} \qquad I_{sdp} = 30.552 \cdot amps$$

This translates to a total transformer secondary current of: $I_{sds} := I_{sdp} \cdot N_i$ $\qquad I_{sds} = 203.681 \cdot amps$

The switching (Mosfet) transistors are rated at 44 amps continuous current. Peak pulse current rating is 165 amps, see data sheet. "A" type supplies use one to carry the full primary current. The B and C supplies use two in parallel for 88 amps max current. The transformer primary and secondary current, for each bank, required by the load depends on the number of banks firing at the same time. The full output current requirements for each supply type and mode (simultaneous/alternate) option are:

| Type/current mode | Total # banks | # firing simultaneously | Secondary current per bank | Primary current per bank |
|---|---|---|---|---|
| * A/200amps simultaneous | 2 | 2 | 100 amps | $100 \cdot \frac{3}{20} = 15 \cdot amps$ |
| A/200amps alternate | 2 | 1 | 200 amps | $200 \cdot \frac{3}{20} = 30 \cdot amps$ |
| B/250 amps simultaneous | 2 | 2 | 125 amps | $125 \cdot \frac{3}{16} = 23.438 \cdot amps$ |
| * B/250 amps alternate | 2 | 1 | 250 amps | $250 \cdot \frac{3}{16} = 46.875 \cdot amps$ |
| * C/750 amps alternate | 6 | 3 | 250 amps | $250 \cdot \frac{3}{16} = 46.875 \cdot amps$ |

The highest current is the B and C type supply with two transistors using 46.8 amps out of 88 max. Next is the A supply running in alternate mode using 30 amps out of 44 amps max (single transistor). The other cases are 50% or less of maximum continuous currents. Any one bank is limited to about 45% maximum duty cycle independent of simultaneous or alternate mode firing. Therefore the transistors are pulsed at 45% max duty cycle, so the use of continuous current ratings is very conservative.

The * represents the way the three supplies are currently wired to operate.

# PWM chip Oscillator analysis

The UC1846 PWM chip uses an internal oscillator circuit to create a ramp signal. This is compared with the error signal at pin 7 to create the pulse width modulated output signal. The varations in perameters from chip to chip make it hard to calculate the frequency and "dead time" for a particular chip. For this reason measured values are used in the above analysis. The following analysis can be used for calculated values if needed but the masured results may vary due

**Theory**: A constant current is used to charge a capacitor Ct (C66 pin 8) to an upper threshold. Then a discharge current is switched on until a lower threshold is reached. The upper and lower threshold is not specified in the data sheet and will vary from chip to chip but was masured to have a delta of about 1.76 volts. "Deadtime" is the discharge time and a sync signal on pin 10 has a width equal to this time. The charge current is set by resistor Rt (R143 pin 9) through a current mirror that is referenced to Vref (pin 2) at 5.1 volts. The voltage at pin 9 across Rt is two diod drops (2*Vd) down from Vref and sets the charge current. During discharge this current subtracts from the discharge current. The discharge current Id is shown in the data sheet as 12 ma but was masured in one case as 7.3 ma. Oscillator frequency is not critical (40Khz +-5 will do) but deadtime and therefore maximum duty cycle must be known to set the inner loop gain.

Use or set the following values: $Rt := 3.01 \cdot k\Omega$ $\quad Ct := 15.35 \cdot nf$ $\quad \Delta V := 1.76 \cdot volts$ $\quad Vref := 5.1 \cdot volts$

Notes: Rt is R143 and Ct is C66. delta V is the peak to peak clock signal measured at pin 8. $Id := 7.324 \cdot ma$ $\quad Vd := 0.745$

| | | |
|---|---|---|
| The voltage across Rt is Vr: | $Vr := Vref - 2 \cdot Vd$ | $Vr = 3.61$ |
| Charge current Ion is: | $Ion := \frac{Vr}{Rt}$ | $Ion = 1.199 \cdot ma$ |
| Discharge current Ioff is: | $Ioff := Id - Ion$ | $Ioff = 6.125 \cdot ma$ |
| Rise time ton is: | $ton := \Delta V \cdot \frac{Ct}{Ion}$ | $ton = 22.526 \cdot us$ |
| Fall time or deadtime toff is: | $toff := \Delta V \cdot \frac{Ct}{Ioff}$ | $toff = 4.411 \cdot us$ |
| Total period is: | $t := ton + toff$ | $t = 26.937 \cdot us$ |
| Oscillator frequency is: | $f := \frac{1}{t}$ | $f = 37.124 \cdot khz$ |
| Deadtime toff sets the maximum duty cycle to: | $dc_{max} := \frac{ton}{ton - toff}$ | $dc_{max} = 0.836$ |

To match a measured supply with this calculation measure Vref at pin 2 and set above then measure Vr at pin 9 and set here. Then Vd will be:

Measured Vr: $Vr := 3.61$ $\quad Vd := \frac{Vref - Vr}{2}$ $\quad Vd = 0.745$

Then Ct can be adjusted for ton and Id can be adjusted for toff as measured.

Or just calculate thus: Measured ton: $ton := 22.526 \cdot us$ $\quad Ct := \frac{ton \cdot Ion}{\Delta V}$ $\quad Ct = 15.35 \cdot nf$

Measured toff: $toff := 4.411 \cdot us$ $\quad Id := \frac{\Delta V \cdot Ct}{toff} + Ion$ $\quad Id = 7.324 \cdot ma$

These values can then be plugged in above to get you in the ballpark. A side note, the data sheet formulas did not seem to be very accurate.

# Variables and constants used

## Power supply parameters

$I_m$ Max Current output
$V_m$ Max Voltage output
$V_c$ Control voltage range

## Filter and load model

$R_o$ Load resistance
$L_o$ Load inductance
$R_f$ Filter inductor resistance
$L_f$ Filter inductor inductance
$R_{esr}$ Filter capacitor effective series resistance
$C_f$ Filter capacitor capacitance

## Transformer model

$R_p$ Transformer and line primary circuit resistance
$N_i$ Current transformation ratio
$N_z$ Reflected impeadance transformation ratio

## Converter model

$Z_o(s)$ Load impedance
$Y_o(s)$ Load admittance
$Z_c(s)$ Filter capacitor impedance and admittance
$Y_c(s)$ Filter capacitor admittance
$Y_{co}(s)$ Load and capacitor in parallel admittance
$Z_{co}(s)$ Load and capacitor in parallel impedance
$Z_l(s)$ Filter inductor impedance
$Z_s(s)$ Total secondary impedance
$Z_p(s)$ Reflected primary impedance
$Z_t(s)$ Total primary impedance
$Y_t(s)$ Total primary admittance

## Pulse width modulator

$ck_{pp}$ PWM peak to peak clock amplitude
$b$ PWM "outputs used" switch
$d_{ck}$ PWM clock divider ratio
$K_{pwm}$ 3X amp gain in PWM chip
$t_{on}$ Clock rise time period
$t_{off}$ Clock fall time period
$t_{ck}$ Total clock period

$f_{ck}$ Clock frequency

## Sampling

$t_s$ Sampler period
$f_s$ Sampler frequency
$G_s(s)$ Sampler transfer function

## Input line

$G_{line}$ Three phase line (gain)
$G_{peak}$ Peak rectifier (gain)

## Primary current sensor

$N_s$ Current sensor turns ratio
$R_s$ Current sense resistor

## Inner current loop

$Gi_{ff}$ Foward path fudge factor
$G_i(s)$ Total foward path gain
$K_i$ Feedback gain constant
$d_i$ Feedback path divider
$Hi_{ff}$ Feedback path fudge factor
$H_i(s)$ Total feedback path gain
$G_{io}(s)$ Open loop gain
$G_{ic}(s)$ Closed loop gain
$G_{il}(s)$ Closed loop line sinsitivity

## Voltage loop

$P_v(s)$ Foward path "Plant" gain
$C_v(s)$ Loop compensator
$G_v(s)$ Total foward path gain
$K_v$ Feedback gain constant
$G_{vo}(s)$ Open loop gain
$G_{vc}(s)$ Closed loop gain
$G_{vl}(s)$ Closed loop line sensitivity

## Current loop

$P_c(s)$ Foward path "Plant" gain
$C_c(s)$ Loop compensator
$G_c(s)$ Total foward path gain
$K_c$ Feedback gain constant
$G_{co}(s)$ Open loop gain
$G_{cc}(s)$ Closed loop gain

$G_{cl}(s)$ Closed loop line sensitivity

# Define functions (Tools)

$\Omega \equiv 1$ $\quad k\Omega \equiv 10^{3}$ $\quad m\Omega \equiv 10^{-3}$ $\quad mh \equiv 10^{-3}$ $\quad uh \equiv 10^{-6}$ $\quad mf \equiv 10^{-3}$ $\quad uf \equiv 10^{-6}$ $\quad nf \equiv 10^{-9}$

$khz \equiv 10^{3}$ $\quad hz \equiv 1$ $\quad amps \equiv 1$ $\quad volts \equiv 1$ $\quad DB \equiv 1$ $\quad us \equiv 10^{-6}$ $\quad mv \equiv 10^{-3}$ $\quad ma \equiv 10^{-3}$

$start \equiv 0.1 \cdot hz$ $\quad end \equiv 100 \cdot khz$ $\quad points \equiv 300$ $\quad n \equiv 0 .. points - 1$ $\quad inc \equiv \dfrac{\log(end) - \log(start)}{points}$ $\quad f_n \equiv 10^{n \cdot inc + \log(start)}$

$M(x) \equiv 20 \cdot \log(|x|)$ $\quad db \equiv 60$ $\quad$ scale $\quad P(x) \equiv \arg(x) \cdot \dfrac{db}{\pi}$ $\quad s_n \equiv i \cdot 2 \cdot \pi \cdot f_n$

**Related documents**

1) "LLUMC Proton Power Supply System Study", Doc # 2001151

2) "Electronic Schematic Magnet Power Inverter" Doc # 2001142

3) "Electric Schematic PDC Output Interface" Doc # 2001143

Note: **If** J12, J13, J11 and J10 sockets are **not** in good condition and "Tight", remove the sockets and solder the componets in.

Remove D72, D73, D78, D79, D85, D86, D90, D91 and replace each with two diodes in series so a two diode drop occurs instead of a one diode drop.

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# Power Supply Modification Report

File: Vtrim
Supply type: A
Magnet type: Vert Trim
Date: 5-17-00

This modification is for a power supply with the following parameters

| | | |
|---|---|---|
| Max Current output | $I_m = 200$ | |
| Max Voltage output | $V_m = 10$ | |
| Load resistance and inductance | $R_o = 35.7 \cdot m\Omega$ | $L_o = 1.6 \cdot mh$ |
| Over current shutdown current: | $I_{sds} = 203.681 \cdot amps$ | |

The following componets provides the "tuning" for the parameters listed above. Perform modifications below if required and install the following parts for this "tuning". See the updated schematics.

| | | | Qty Reqd. |
|---|---|---|---|
| **Inner current loop gain** | IC40 feedback resistor: | $R160 = 1.6 \cdot k\Omega$ | 1 |
| **Voltage loop compensator** | R148=R149=R151=R210: | $R210 = 20 \cdot k\Omega$ | 4 |
| C108 is installed in J10 near SW1. C109 is added in series with R248 across resistor R149. | C108=C109: | $C108 = 1 \cdot uf$ | 2 |
| R247 is installed in J11 near SW1. | R247=R248: | $R247 = 0.665 \cdot k\Omega$ | 2 |
| | C67=C68: | $C67 = 100 \cdot nf$ | 2 |
| **Current loop compensator** | R196=R222: | $R222 = 20 \cdot k\Omega$ | 2 |
| C107 is installed in J13 near SW3. | | $C107 = 1 \cdot uf$ | 1 |
| R246 is installed in J12 near SW3. | | $R246 = 44.2 \cdot k\Omega$ | 1 |
| | | $C93 = 100 \cdot nf$ | 1 |
| **Over current shutdown** | | $R165 = 20 \cdot k\Omega$ | 1 |
| | | $R220 = 6.19 \cdot k\Omega$ | 1 |

## Modifications

Check to see if the following modifications to the MPI board have been done. If not, perform the following procedure to bring the board up to date.

Remove the following parts: C73, C74, C77, C79, C80, C84, C86, C87, C96, C98, C99, C102, C104, C105, C88, IC40 (OP77), IC46 (MC1458).
Remove (unplug) SW1 and SW3 dip switches.

Replace OP-AMPs: Install AD711 op-amp for IC40
Install AD712 op-amp for IC46

Replace and/or add the componets listed in the "tuning" section above. Some of the parts are new and installed as follows:

R246 in J12, C107 in J13, R247 in J11, C108 in J10. R248 is soldered in series with C109 and the pair soldered across R149. Keep leads short and install on componet side of board (see new schematics)

Note: Move any large filter capacitors from output bus to bus bars in front of LIM! (A supply has two 1000uf)